“Learning About Resilient Futures” Workshops for Fire/Forest Managers

Co-sponsored by Joint Fire Science Program research project (16-3-01)
and the Northern Rockies Fire Science Network
Facilitated by Anne E. Black, USFS

18-19 February 2020: USGS Northern Rocky Mountain Science Center, 2327 University Way, Bozeman
20-21 February 2020: University Center (UC 225), University of Montana, 32 Campus Drive, Missoula

AGENDA

<u>**DAY 1**</u>

8:30-9:00	**Welcome and purpose (**Monica Turner)
9:00-9:30	**Introductions, agenda review, reminders**
	Dimensions of resilience
9:30-9:45	• Project overview and recap workshop #1 (Monica Turner)
9:45-10:00	• Resilience terminology in science and management (Adena Rissman)
10:00-10:30	**Group discussion** – framing resilience for forests of the Northern Rockies forests
10:30-10:45	BREAK
	Learning about resilient futures: Setting the stage
10:45-10:55	• Why models, and why iLand? (Rupert Seidl)
10:55-11:05	• Adapting iLand to the Northern Rockies (Kristin Braziunas, Zak Ratajczak)
11:05-11:15	• Generating climate-fire scenarios for the Northern Rockies (Leroy Westerling)
11:15-11:30	**Discussion and Q&A**
11:30-12:00	GET LUNCHES, RETURN FOR WORKING LUNCH
	Climate, fire and forest resilience – no management
12:00-12:30	• 21st century forest resilience in the GYE, from stands to landscapes (Monica Turner)
12:30-12:45	• Tipping points and fire rotations (Zak Ratajczak)
12:45-1:00	**Discussion and Q&A**
1:00-1:10	• Implications for forest wildlife habitat (Tyler Hoecker)
1:10-1:30	• 21st century forest resilience in Crown of the Continent (Tyler Hoecker)
1:30-2:00	**Group discussion** – interpreting model results and multiple dimensions of resilience
2:00-2:15	BREAK
	Climate, fire and forest resilience – with management
2:15-2:30	• Fire suppression decisions (Adena Rissman)
2:30-2:45	• Consequences of fire suppression for forest resilience (Monica Turner)
2:45-3:00	**Group discussion**
3:00-3:30	• Fire in the wildland-urban interface (Kristin Braziunas)
3:30-4:00	**Small group discussions** – ecosystem services, management, in WUI
4:00-4:15	Groups report out
4:15-4:30	**Group discussion** – overall summation for the day, prompts to ponder over night
4:30	ADJOURN
6:00	**Dinner** (optional, not provided; team + participants; location TBD)

AGENDA

DAY 2

8:30-9:00	**Welcome and reflections** – thoughts from over night
	Scaling up from landscapes to region
9:00-9:15	• Projecting forest transitions (Rupert Seidl)
9:15-9:30	• Northern Rockies climate-fire projections (Leroy Westerling)
9:30-10:00	**Group discussion** – reactions, interpretations
10:00-10:15	BREAK
	Synthesis
10:15-11:30	**Structured discussions –** perceptions and meaning of results for forest and fire management, communicating to the public, outstanding questions and knowledge gaps
11:30-11:55	**Post-workshop participant survey** (Adena Rissman) **Workshop evaluation** (NRFSN)
12:00	ADJOURN

Learning About Resilient Futures
Workshops for Fire/Forest Managers

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18-19 February 2020, Bozeman, MT
20-21 February 2020, Missoula, MT

Presenters

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Kristin H. Braziunas, University of Wisconsin-Madison (PhD student), braziunas@wisc.edu

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What makes for a resilient landscape? Climate, fire and forests in the Northern Rockies
JFSP Proposal 16-3-01-4; submitted 13 November 2015

Proposal Summary

Resilient landscapes are a fundamental goal of the National Cohesive Wildland Fire Management Strategy, yet defining, measuring and managing for resilience remain major challenges. Ecological resilience theory is well developed, but how to operationalize resilience in actual landscapes is unclear, especially in a no-analog future. Fire and forest managers would benefit from knowing how to measure resilience; where, when and why resilience may be lost; and what management options can promote resilience. We propose to quantify ecological and social dimensions of resilience for Northern Rocky Mountain forests and to develop innovative scientific methods for operationalizing forest and landscape resilience concepts. Guided by participatory workshops with stakeholders, we will determine how 21st-century climate and fire regimes are likely to alter the resilience of Northern Rocky Mountain forests and identify management options likely to promote landscape resilience under a range of possible futures. First, we will engage fire, fuels and resource managers and stakeholders at a "*Dimensions of Resilience*" workshop to identify social and ecological dimensions of resilience–i.e., the multiple characteristics they want to sustain throughout the 21st century–and management options to explore given changing climate and fire regimes. Informed by this stakeholder input, we will then combine state-of-the-art projections of future climate and fire with extensive data on post-fire forest dynamics to model alternative future scenarios and evaluate ecological and social dimensions of resilience through the 21st century at three spatial scales.

(i) Stand: How and why might warming climate and changing fire regimes push forest stands over a tipping point? Fire is the dominant disturbance shaping Northern Rockies forests, and post-fire tree regeneration is fundamental to stand-level resilience. We will evaluate mechanisms behind tipping points in a range of future climate-fire scenarios, using the empirically based Forest Vegetation Simulator (Climate-FVS) and a next-generation process-based model (iLand) that can respond dynamically to novel conditions.
(ii) Landscape: Where and when might projected changes in climate and fire activity interact with management to enhance or erode landscape resilience? Abrupt transitions at the stand level may scale up and erode landscape resilience, or they may smooth out over larger areas as forest dynamics respond to changing conditions. We will simulate an array of representative Northern Rockies landscapes (areas of wildland-urban interface, production forestry, and wilderness) and potential management options using the spatially explicit implementation of iLand.
(iii) Region: How do stand and landscape indicators of resilience scale to the Northern Rockies ecoregion, and what geographical areas are most likely to be vulnerable or resilient to changing climate and fire regimes? We will develop innovative statistical approaches to extrapolate stand- and landscape-level results and assess regional resilience. Probabilistic maps of the resilience indicators generated with stakeholders will be produced to identify geographic areas at risk for crossing tipping points under alternative scenarios.

Finally, informed by model and scenario results, we will re-convene with stakeholders at a "*Learning about Resilient Futures*" workshop to jointly interpret effects of changing climate, fire and management on dimensions of landscape resilience articulated at the first workshop and to specify outreach products. Goals include understanding conditions and management options that promote resilient landscapes and elucidating synergies and tradeoffs among multiple dimensions of resilience. This project will directly benefit fire and forest managers by making resilience concepts useful for managing landscapes during times of profound environmental change.

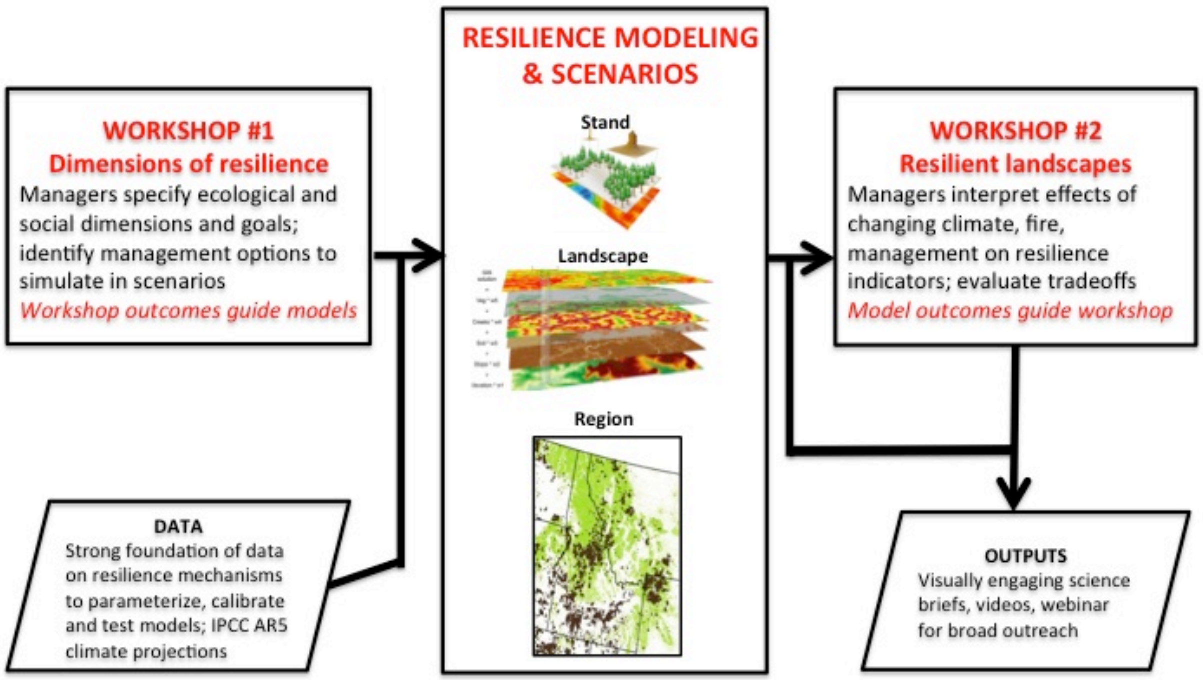


Fig: Flow chart of stakeholder-driven exploration of resilience in Northern Rocky Mountain forests.

DIMENSIONS OF RESILIENCE

Project Overview and Workshop 1 Recap

Monica Turner

Your concerns guided our work (Bozeman and Missoula, February 2017)

- Future scenarios
- Response variable
- Management options
- Landscapes

Resilience to what?

- Increasing fire size, frequency, severity
- Lengthening fire season
- Changing climate

Resilience of what?

- Forest landscape diversity
    - Mix of stand structures and successional stages?
    - Old-growth or mature forests?
    - Wildlife habitat (biodiversity)?
- Postfire tree regeneration
    - Changing species composition? Aspen?
    - Moist-forest species (e.g., cedar-hemlock?)
    - Conversion of forest to grassland?
- Communities
    - Increasing WUI and fire risk
    - Ecosystem services

Fire and forests management options

- Effects of fire suppression vs. wildland fire use
    - What if historical fires had been suppressed? Would the landscape be different now?
    - Will keeping small fires small reduce subsequent fire?
- Fuels reduction and non-commercial thinning
    - Especially in the WUI, where increased fire risk is a growing challenge for forest and fire manager

But…we couldn't do it all

- Pests and pathogens
- Smoke
- Invasive species (most were non-forest)
- Clean streams, trout habitat
- Riparian management
- Assisted tree migration
- Grazing
- Economics of local markets

Resilience terminology in science and management

Adena Rissman

Context: To better understand the implications of the word resilience for western forest and fire management, we explored its emerging use in a large body of policy and management documents produced between 1980 and 2016.

Questions: Comparing 1,487 scientific journal articles and 139 western U.S. Forest Service (USFS) planning documents we asked:
(1) how has the use-rate of the word resilience changed over time?
(2) are changes in the use-rate of the word resilience correlated with shifts in terminology associated with environmental values, complex systems theory, or environmental change?
(3) how does the use of the word resilience compare between science and management documents?

Key findings: The word resilience has been used in these documents since the 1980s but its use sharply increased in both contexts between 2009 and 2011. The use-rate trends differ between science and management documents and do not appear to be associated complex systems terms but do seem associated with increases in the use of terms "climate change" and "adapt" and biocentric values. Although there are differences in how resilience is used between science and management documents, the shared meaning is a hopeful framing for adapting forests to changing conditions.

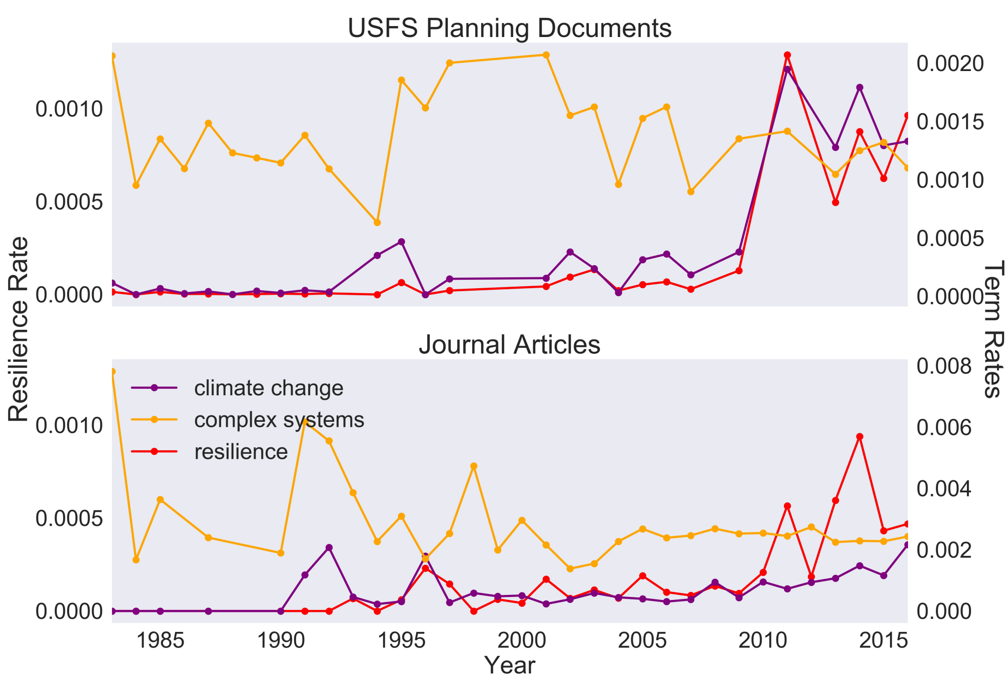


Figure: Resilience (red) use rate in documents has increased, especially tied to climate change adaptation in USFS plans and Environmental Impact Statements.

Citation*: Selles, Owen and Adena R. Rissman. 2020. Content analysis of resilience in forest fire science and management. Land Use Policy. In press.*

LEARNING ABOUT RESILIENCE FUTURES: SETTING THE STAGE

Why modeling, why iLand?

Rupert Seidl, Werner Rammer

Simulation modeling is a central tool for quantifying and projecting forest resilience. Simulation models also form the methodological backbone of the JFSP project "What makes for a resilient landscape? Climate, fire and forests in the Northern Rockies". We here applied models in two different ways: First, conducting simulation experiments manipulating individual drivers, we used models to improve our understanding of how specific processes (e.g., seed supply, seed delivery, and seedling establishment) contribute to forest resilience (modeling for understanding). Second, we ran model-based scenario analyses to assess the impacts of potential future climate and fire scenarios on forest development and the ecological resilience of forest ecosystems in the Northern Rockies (modeling for projection). Such model-based scenario analyses are not only suited to quantify the impact of environmental changes, but can also be used to investigate how effective different management measures are to counter these impacts.

To study the resilience of forest landscapes to changing climate and fire regimes we here used iLand, the individual-based forest landscape and disturbance model (Seidl *et al.*, 2012). The key advantage of using a process-based model such as iLand over empirical approaches (e.g., FVS) is that they are better able to capture the emergence of novel ecosystems under no-analog future conditions (Gustafson, 2013). iLand is a spatially explicit model operating at the grain of individual trees, and simulating forest dynamics based on first principles of ecology. iLand also contains a flexible management interface which allows for the implementation of a wide range of treatments, which interact dynamically with the emergent vegetation development in the simulation (Rammer & Seidl, 2015). Wildfire ignitions and potential maximum fire size were determined based on fire – climate relationships (Westerling *et al.*, 2011). Fire spread was simulated dynamically at a grain of 20m cells, and realized fire sizes as well as fire perimeters are thus an emergent property of the simulations, accounting for the influence of wind topography, and fuels. Fire severity is simulated based on fuel load and fuel moisture and considers effects of forest structure and composition.

Citations

Gustafson, E.J. (2013) When relationships estimated in the past cannot be used to predict the future: using mechanistic models to predict landscape ecological dynamics in a changing world. Landscape Ecology, 28, 1429–1437.

Rammer, W. & Seidl, R. (2015) Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes. Global Environmental Change, 35, 475–485.

Seidl, R., Rammer, W., Scheller, R.M. & Spies, T.A. (2012) An individual-based process model to simulate landscape-scale forest ecosystem dynamics. Ecological Modelling, 231, 87–100.

Westerling, A.L., Turner, M.G., Smithwick, E.A.H., Romme, W.H. & Ryan, M.G. (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences of the United States of America, 108, 13165–13170.

Adapting iLand for the Northern Rockies

Kristin Braziunas, Zak Ratajczak

Context and Aims: iLand has been adapted to a number of temperate forests globally, but until recently, not the US Northern Rocky Mountains. Over the course of this project, we extended iLand to the Northern Rockies by:

- Parameterizing regional tree species using published empirical studies.
- Tuning and evaluating the performance of tree species, using independent datasets to calibrate and evaluate simulated forest structure and composition.
- Incorporating new parameters to represent forest resilience to fire and climate change, including serotiny (lodgepole pine), resprouting (aspen), and seedling drought tolerance.
- Upscaling from stand (1 ha) to landscape (45,000 to 65,000 ha) to region (3,000,000 ha).
    - Incorporates spatially explicit data for initial vegetation, elevation, soils, recent fires (1984-2016), and recent historical and future climate projections.
- Tuning the iLand fire module to match fire regimes in the Northern Rockies, in terms of burn severity, fire size distribution, and fire shape.
- Merging future fire projections by Westerling et al. with iLand.

We took care that general stand dynamics followed empirical observations over space and time based on comparisons with published field data, forest inventory and analysis (FIA) data, stand development using the Forest Vegetation Simulator (FVS), and existing vegetation maps. Fire regimes were compared against Monitoring Trends in Burn Severity (MTBS).

Tree species parameterized for the US Northern Rockies

Started with Greater Yellowstone species...

- Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)
- Engelmann spruce (*Picea engelmannii*)
- Lodgepole pine (*Pinus contorta* var. *latifolia*)
- Quaking aspen (*Populus tremuloides*)
- Subalpine fir (*Abies lasiocarpa*)
- Whitebark pine (*Pinus albicaulis*)

...adding species throughout Northern Rockies

- Grand fir (*Abies grandis*)
- Ponderosa pine (*Pinus ponderosa*)
- Subalpine larch (*Larix lyallii*)
- Western hemlock (*Tsuga heterophylla*)
- Western larch (*Larix occidentalis*)
- Western red cedar (*Thuja plicata*)
- Western white pine (*Pinus monticola*)

Citation: *Braziunas,K.H., W.D. Hansen, R. Seidl, R. W. Rammer, and M.G. Turner. 2018. Looking beyond the mean: Drivers of variability in postfire stand development of conifers in Greater Yellowstone. Forest Ecology and Management 430:460-471*

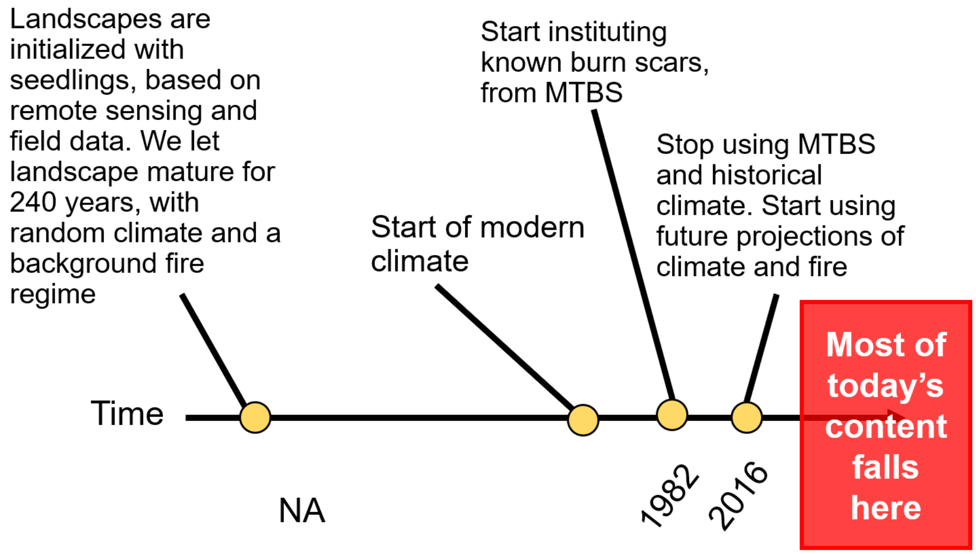


Fig: A schematic of our process for "spinup," which generates realistic initial forest conditions as of 2016. In brief, we generate a mixed age forest landscape, as of year 1950, then incorporate historical climate from 1950 to 2016 and known fire scars from 1982 to 2016. Starting in 2016, future climate and potential future fires are incorporated from the Westerling et al. projections (this workshop).

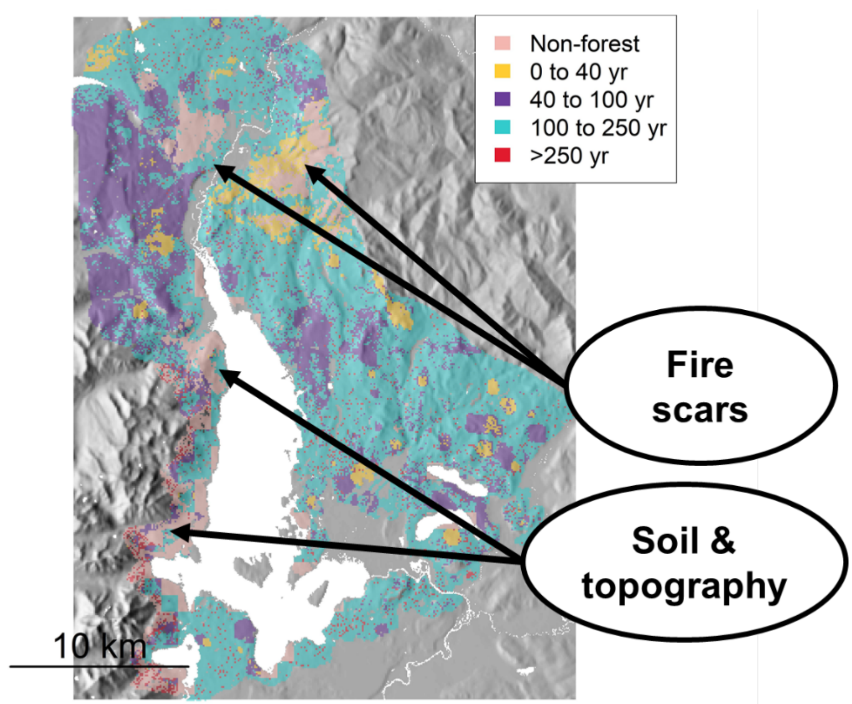


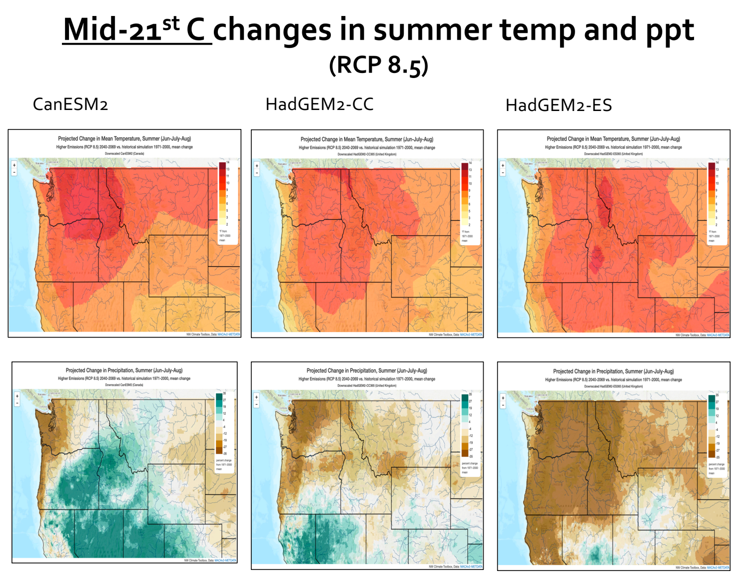
Fig: An overhead view of our landscape centered on Grand Teton National Park. Colors denote stand age. All grey areas not part of the simulated landscape, although "burn in" from these areas is accounted for in all runs from 2016 onwards. Note that you can see clear fire scars to the north of Jackson Lake. Topographic effects, specifically thin soils, are clear on the west bank of Jackson lake, shown by areas with no forest (pink color).

Generating climate-fire scenarios for the Northern Rockies

Leroy Westerling

For this study, we selected three general circulation models (GCMs) from the IPCC 5th assessment and two emissions pathways to represent alternative future climate scenarios to generate potential fire number, size and location in Northern US Rocky Mountain forests. The three GCMs show similar warming trends but vary substantially in precipitation, as illustrated below for summer (June-July-August) precipitation in mid-century (https://climate.northwestknowledge.net/MACA/tool_summarymaps2.php). The CanESM2 model projects warmer temperatures with increased precipitation. The HadGEM2-CC and HadGEM2-ES models both project drier conditions. The timing, severity and duration of summer drought varies between the HadGEM2 models, but aridity becomes more pronounced in the HadGEM2-ES model. Spatial variation in projections, especially for precipitation, is also apparent across the region.

Statistical models relating fire activity to temperature, precipitation and topography were developed following methods described by Westerling et al. (2011). These models were then used to simulate 20 scenarios of fire number, location, and size on a monthly basis through 2100 for each of six GCM x RCP combinations. As in the earlier study, these models reflect fire probabilities based on climate and topography alone (i.e., fuels are not included). In our current study, feedbacks between vegetation and fire are represented: statistical fire projections were used to drive landscape-level iLand simulations, and realized fire sizes and severities depended on weather, topography and fuels. Statistically simulated fires were also annualized and allocated to the landscape in order to estimate implied fire rotations without vegetation feedbacks.



Citation: *Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme and M. G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences 108:13165-13170.*

CLIMATE, FIRE AND FOREST RESILIENCE--NO MANAGEMENT

Effects of climate and fire on postfire regeneration failure of lodgepole pine and Douglas-fir in Greater Yellowstone (Monica Turner)

Context: As the frequency and size of stand-replacing fires increases with climate warming, postfire regeneration is necessary (but not sufficient) for forests to be resilient. However, how postfire tree regeneration success will respond to these changes is uncertain. Regeneration could fail if fires re-occur before trees are mature or if the sizes of high-severity burn patches exceed dispersal distance. And even if seed is available, trees might not regenerate if postfire climate years are too hot and dry.

Aims: We used iLand at the stand level to determine how the success or failure of postfire tree regeneration is influenced by fire-return interval (FRI), distance to seed source (related to fire size), and postfire climate. We simulated all combinations of these conditions (with replications, because the model is probabilistic), then assessed lodgepole pine and Douglas-fir regeneration 30 years after stand-replacing fire. We 50 stems/ha (saplings + trees) as the threshold density needed for regeneration to be considered successful.

Key findings: Trees did regenerate under most combinations, but Douglas-fir was more vulnerable to regeneration failure than lodgepole pine. When tree regeneration failed, it was usually in stands >500 m from a seed source. Serotinous lodgepole pine stands were very resilient, and regeneration only failed for very short (20 yrs) FRI and long distances (> 500 m) from seed source. Douglas-fir regeneration increased with warming, and lodgepole pine regeneration was unaffected by the warmer climates simulated in this study. Changes in the fire regime had a much larger effect on postfire regeneration than did climate.

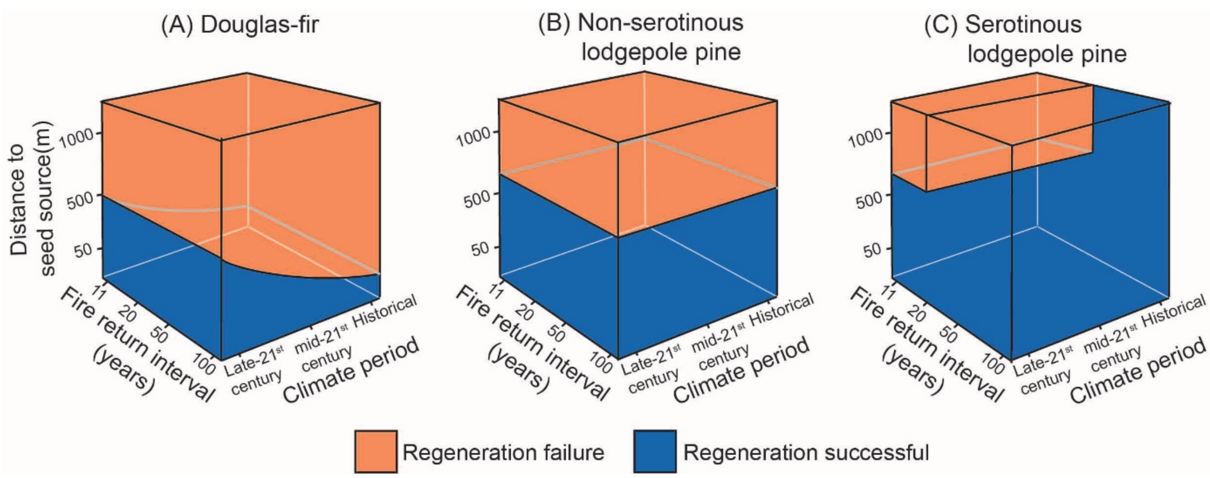


Figure: Combinations of postfire distance to seed source, fire return interval, and climate that can cause regeneration failure for Douglas-fir and lodgepole pine. Regeneration failure generally occurred in stands far from seed for Douglas-fir and non-serotinous lodgepole pine, and following short-interval fires -for serotinous lodgepole pine.

Citation: *Hansen, W.D., K.B. Braziunas, W. Rammer, R. Seidl, and M.G. Turner. 2018. It takes a few to tango: Changing climate and fire can cause regeneration failure in two subalpine conifers. Ecology, 99:966-977.*

Stand-level consequences of short-interval fire in Greater Yellowstone
Monica Turner

Context: A key lesson from the 1988 Yellowstone fires was that the forest ecosystems were very resilient even to large, high-severity fire. The forests recovered quickly without intervention. Furthermore, most wood remained in the ecosystem as standing dead trees and logs. Following stand-replacing fires, the subalpine forests need about 100 years to recover their carbon stocks, and produce seeds sufficient to re-establish after the next fire. With climate warming, however, our earlier work (Westerling et al. 2011) suggested that the hot, dry weather conducive to large fires would become very frequent, and fire rotations could potentially drop to < 30 yrs by the late 21st century. Such short rotations are well outside historical ranges, and what this would mean for forest resilience had not previously been studied.

Aims: By reburning young forests that regenerated after the 1988 and 2000 fires, the Maple and Berry Fires of summer 2016 created a natural experiment for studying effects of short-interval fire. Young stands were merely 16 or 28 years old when they reburned. We conducted field studies during summer 2017 to quantify burn severity, initial tree regeneration and carbon stocks in these reburns. We also used iLand at the stand level to simulate carbon recovery in each of our field plots to compare carbon recovery with and without the reburn. We initialized the model with our field data, and ran simulations for 150 years assuming historical climate and no subsequent disturbance.

Key findings: With reburning, fire severity was higher, initial tree regeneration was much lower, and recovery of live tree carbon was delayed by about 80 years. Downed coarse wood and total aboveground C stocks did not recover over the 150 year simulation. Thus, a single short-interval fire alone can disrupt the normal fire-recovery cycle and cause substantial delays in carbon recovery, which erodes forest resilience.

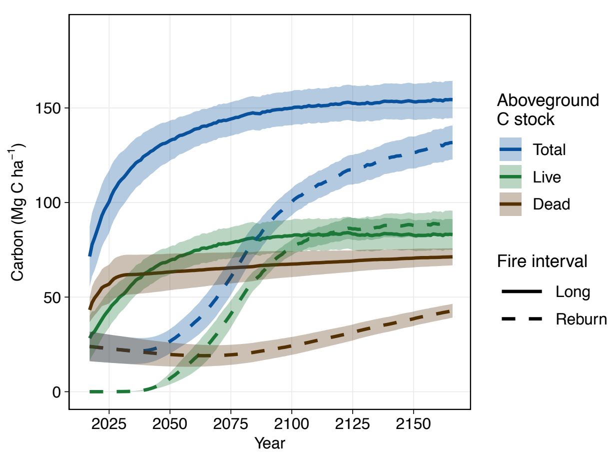


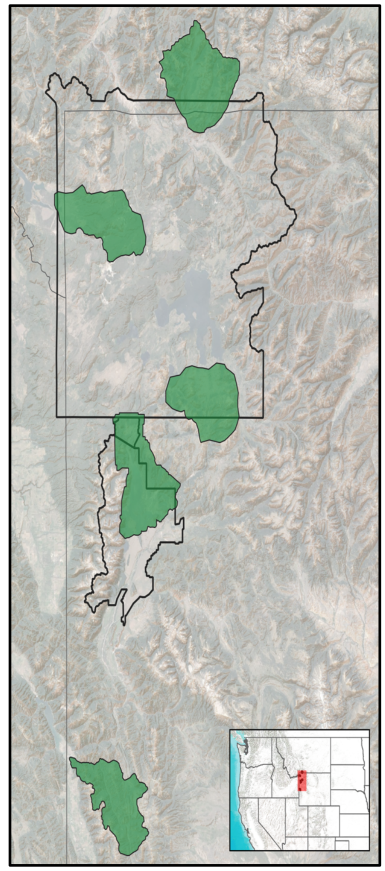
Figure: Simulated recovery of aboveground carbon stocks in young (< 30 yr) lodgepole-pine dominated stands (*n* = 18) with (dashed line) and without (solid line) the 2016 reburns.

Citation: *Turner, M. G., K. H. Braziunas, W. D. Hansen, and B. J. Harvey. 2019. Short-interval fire erodes the resilience of subalpine lodgepole pine forests. Proceedings of the National Academy of Sciences 116:11319-11328.*

21st-Century forest resilience in Greater Yellowstone landscapes

Monica Turner

Context and aims: Although they have been resilient historically, warming climate and novel fire regimes could erode forest resilience (ability to rebound from disturbance) and even lead to forest collapse (abrupt loss). However, the magnitude and tempo of likely changes in species composition, stand-age distributions, forest structure (e.g., tree density, basal area, carbon stocks) and forest extent are difficult to anticipate. Will changes be gradual or abrupt, synchronous or staggered? Can any indicators of forest resilience predict forest collapse? We addressed these questions in well-studied forests of Greater Yellowstone using iLand. We simulated forest dynamics through 2100 in five representative landscapes (1-ha resolution; see figure) with six projected future climates (three GCMs and two RCPs, 4.5 and 8.5) and 20 probabilistic scenarios of annual potential fire sizes and locations for each climate-landscape combination (*n*=600 runs). Fire spread and severity were a function of available fuel load, weather, and species traits; tree regeneration varied with propagule pressure (including serotiny), resprouting (for aspen), seed dispersal, and climate controls on seedling establishment and growth.



Key findings:

- Annual area burned increased substantially in warmer-drier climate conditions, but forests maintained resilience if increased precipitation accompanied warming.
- *With warming and more fire*: species range contractions (e.g., spruce-fir, lodgepole pine) were often abrupt, whereas species range expansions (e.g., Douglas-fir, aspen) were gradual.
- Forests shifted toward younger ages. The age of the oldest stands declined from 200-300 yrs to < 100 yrs by mid-to-late 21st century.
- Changes in forest structure were profound. Abrupt, synchronous declines in tree density, basal area, leaf area index, and aboveground live carbon stocks often occurred before 2050, with dense conifer forests becoming very sparse (<200 trees/ha).
- Forest extent (areas with >50 trees/ha) ratcheted down with increased fire. Sparse forests could not recover with increasing fire frequency, leading to collapse of 50-75% of forested areas by late century in warm-dry climate scenarios. Forest loss was driven primarily by increased fire, and abrupt declines in stand structure preceded forest collapse by 25-30 years.
- Forest structure is a measurable and sensitive indicator of forest resilience in subalpine conifer forests with potential to warn of where and when forests could collapse.

Unpublished data (please do not cite)*: Turner, M. G., Z. Ratjczak, K. H. Braziunas, W. D. Hansen, T. J. Hoecker, W. Rammer, R. Seidl, and A. L. Westerling. Indicators of forest resilience in a warmer world with more fire. (In preparation).*

Tipping points in Greater Yellowstone forests with increasing wildfire activity

Zak Ratajcazak

Background and aim: A key unknown is whether forests will respond incrementally to increasing wildfire potential as climate warms, or exhibit tipping points, where small increases in fire activity result in sharp declines in forest resilience. Across all of our simulations, fire rotations—the number of years it takes to burn an area equal to each landscape—ranged from 10 to 250 years. We leveraged this range of variation to assess if the relationship between fire rotation and forest state (forest extent, stand structure, carbon pools) is linear or exhibits thresholds, captured by a split-linear model.

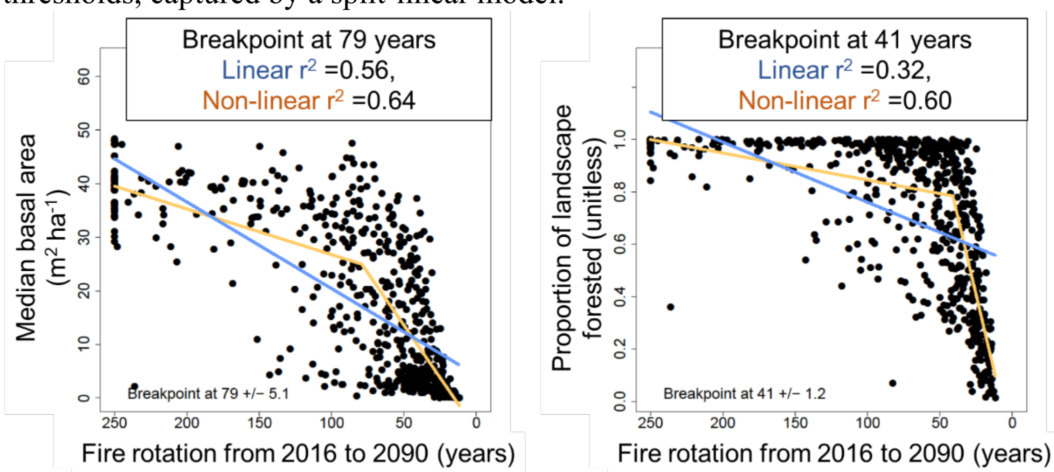


Figure caption: Two examples of relationships between fire rotation, and forest state, measured as basal area (left) or the spatial extent of forests (right). Each point is one simulation from one landscape. The blue line is a linear fit, whereas the orange line shows a split-linear model.

Key Findings: By the year 2100, simulated forest extent, tree density, basal area, and aboveground carbon pools all exhibited non-linear relationships with fire rotation (see Figure for two examples). As fire rotation decreases, forests go through a series of tipping points, with stand density and basal declining first, then aboveground carbon storage, and finally, forested area (see Table 1 for specifics). For example, as fire rotation decreases from 100 years to 40 years, forest extent declines slightly from ~100% to ~80%, but when fire rotation decreases from 40 years to 10 years, forest extent declines from ~80% to ~10%. Similar thresholds are apparent by the mid-century and for individual tree species. The implication is that subalpine forests may be resilient to changing fire regimes until a fire rotation threshold is passed, at which point forest resilience declines steeply. Simulations with lower greenhouse gas emissions were consistently less likely to cross these key thresholds.

Table: Fire rotation thresholds

Response variable	Fire rotation threshold	Forest state above threshold	Forest state below threshold
Forest area	40 years	>80% area	5 to 20 % area
Stand density	76 years	>200 trees per ha	0 to 5 trees per ha
Basal area	79 years	>130 ft^2 per acre	0 to 9 ft^2 per acre
Above ground carbon	80 to 60 years	>150 Mg C per ha	30 Mg C per ha

Unpublished data (please do not cite)*: Ratajczak et al. (In preparation)*

Implications for forest wildlife habitat

Tyler Hoecker

Future fire regimes will impact habitat for forest specialists

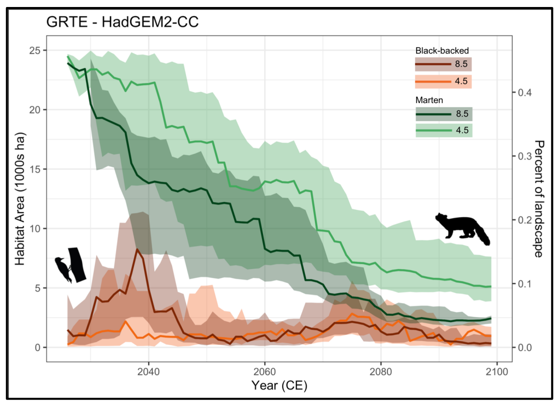
Wildlife populations are vulnerable to projected 21st-century changes due both to direct shifts in environmental conditions and through novel disturbance regimes that affect habitat quantity and quality. In the northern US Rocky Mountains, fire activity is expected to increase substantially, in many places catalyzing transitions in mature subalpine forests to alternative land cover types.

We combined habitat models with forest simulations to quantify future habitat

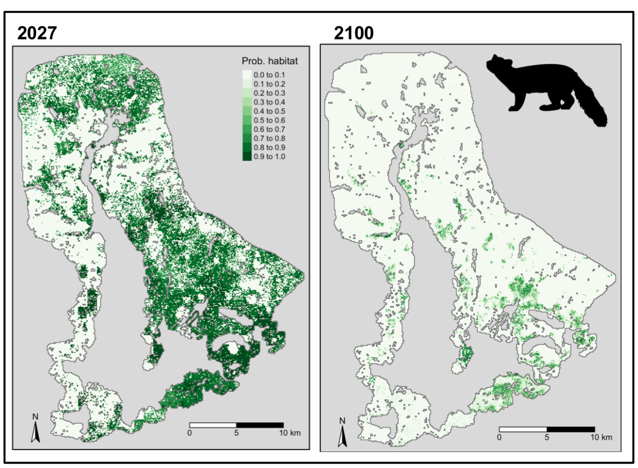
We asked how alternative future scenarios of warming climate and increased fire in the GYE could affect habitat area for American pine marten (PIMA, *Martes americana*) and Black-backed woodpecker (BBWO, *Picoides arcticus*) during the 21st century. BBWO is a burned-forest specialist, favoring severely burned (>90% mortality) stands of dense (>200 trees/ha) large (>20 cm diameter) conifers, which provide abundant food and nesting resources. PIMA favors late-seral structurally complex conifer forests (75% tree age > 80 years) with large trees (>20 cm diameter) and areas of continuous canopy cover (basal area >18 m^2 ha^{-1}) that support their prey. We developed rule-based habitat suitability models and combined them with projected forest structures for two ~500 km^2 landscapes (Northern Yellowstone National Park-Custer-Gallatin National Forest; and Grand Teton National Park) simulated using iLand. We estimated potential habitat area for both species through 2100 for several future climate scenarios.

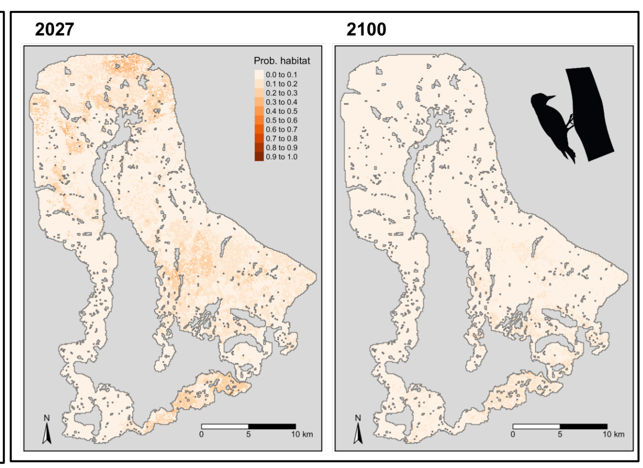
Dry scenarios with increased fire activity reduced habitat availability

In scenarios where warmer, drier conditions promoted more fire (e.g., HadGEM2-CC, shown in figures), BBWO habitat increased through the mid-21st century to a maximum of <5% of the landscape, then declined to <1% as tree size, density and cover declined. PIMA habitat area declined steadily from >10% of the landscape in 2020 to ~5% in 2090 as tree density, age and cover declined. However, when precipitation also increased with warming and fire activity did not (e.g., CanESM), BBWO and PIMA habitat both declined continuously, but PIMA habitat was higher in 2100 than dry scenarios.



Fire-driven changes in forest landscapes will affect wildlife species differently and may lead to surprising changes in 21st-century wildlife assemblages.

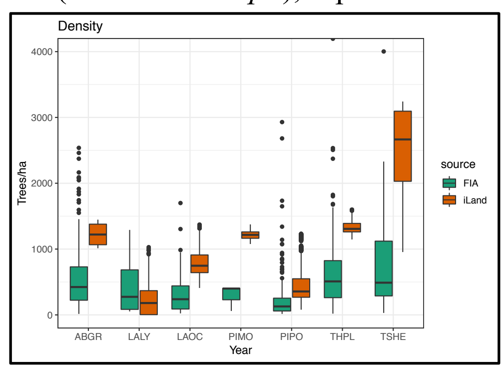




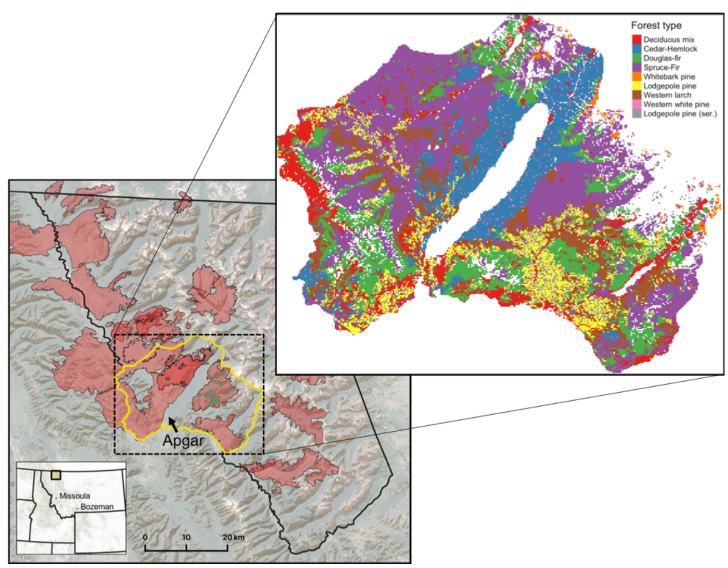
Anticipating 21st century forest dynamics in the Crown of the Continent (Tyler Hoecker)

The response of subalpine forests in the Crown of the Continent to 21st-century environmental change will reflect their diverse ecology. Recent fires in Glacier National Park offer early examples of expected changes in regional fire regimes that could erode forest resilience: short-interval fires that reburn young forests, and high-severity fires that burn old-growth forests not usually exposed to fire. We seek to anticipate how projected changes in climate and fire will impact forest ecosystems in the Crown of the Continent (CC). These subalpine forests include a diverse suite of tree species and exhibit steep environmental gradients, complementing our work in the GYE.

Development of iLand, a forest simulation model, in this region is ongoing
Adapting iLand to the CC landscape requires similar development, calibration and validation as for the GYE, including parameterization of a unique assemblage of tree species. We are testing parameters in the CC landscape for species that also occur in the GYE, including serotinous and non-serotinous lodgepole pine (*Pinus contorta* var. *latifolia*), Douglas-fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), aspen (*Populus tremuloides*), and whitebark pine (*Pinus albicaulis*). We are adding western larch (*Larix occidentalis*), western white pine (*Pinus monticola*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). Stand-level model runs to evaluate the model against data are ongoing, and initial results are encouraging (see boxplot of stand density).



With input from Glacier National Park personnel, we identified a ~500 km^2 (~200 mi^2) focal landscape around Lake McDonald. It encompasses much of the CC's forest diversity including mesic old-growth cedar-hemlock forests, fire-adapted lodgepole pine and western larch, mixed spruce, subalpine fir, and Douglas-fir stands, and treeline stands of whitebark pine. One challenge is to reproduce the contemporary landscape, which is comprised of young stands that regenerated after extensive recent fire activity plus ancient forests established during the Little Ice Age ca. 1500 CE. Once iLand is fully calibrated, we will implement the same set of future climate scenarios as in the GYE (3 GCMs x 2 RCPs x 20 realizations of potential future fire activity).



Unpublished data (please do not cite)*: Hoecker et al. (In preparation)*

CLIMATE, FIRE AND FOREST RESILIENCE—WITH MANAGEMENT

Selecting other than full suppression: Manager choice of suppression method varies with management, socioeconomic, environmental, and fire conditions

Adena Rissman

Context: Managers may select other than full suppression to promote responder safety, reduce firefighting costs, and enhance the beneficial effects of fire. However, threats to human safety, property, and resources, along with public pressures and agency cultures often lead to full suppression choices.

Aims: This study aims to identify the contexts in which managers select full suppression or other strategies of point protection, confine, or monitor during fire incidents. We examine relationships between suppression decisions and key management, socioeconomic, environmental and fire characteristics using qualitative and quantitative methods in the northern Rocky Mountains. We develop regression analyses of fire incident reports from 374 fires between 2008 and 2013 and interview fire managers.

Key findings: Full suppression was associated with management variables such as non-federal land jurisdiction, regional and national incident management teams, and earlier report dates within the fire season, along with higher housing density, human-caused ignitions, low to moderate terrain, grass and shrub fuels, and greater fire size. Interviews with eight fire managers provides decision-making context for these variables within the study period and outlooks for future manager decision space.

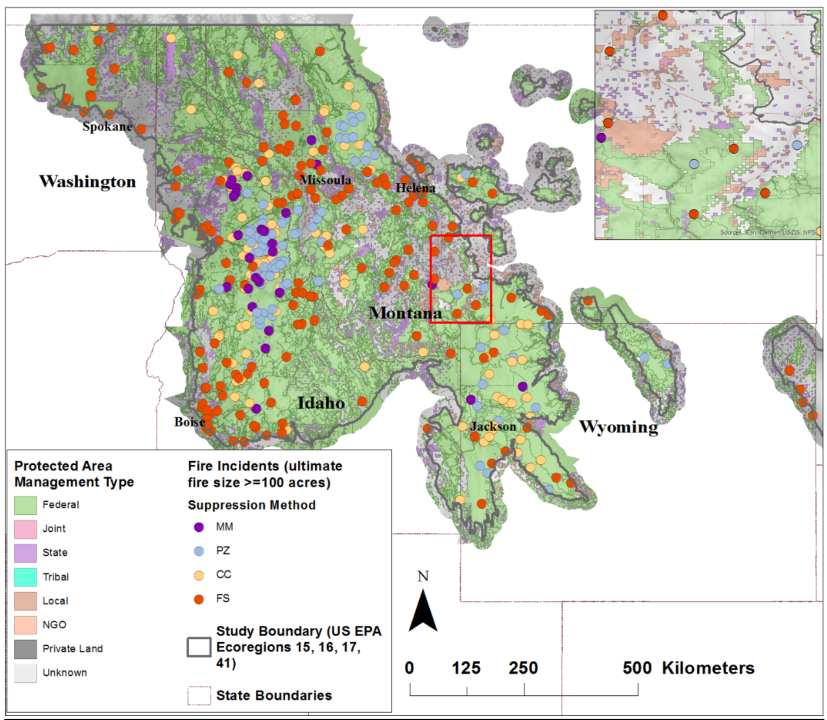


Figure: Map of suppression method in the northern Rocky Mountains, 2008-2013.

Citation: *Daniels, M.C., Braziunas, K.H., Turner, M.G., Ma, T.F., Short, K.C., Rissman, A.R. In preparation. Manager choice of suppression method varies with management, socioeconomic, environmental, and fire conditions. (In preparation)*

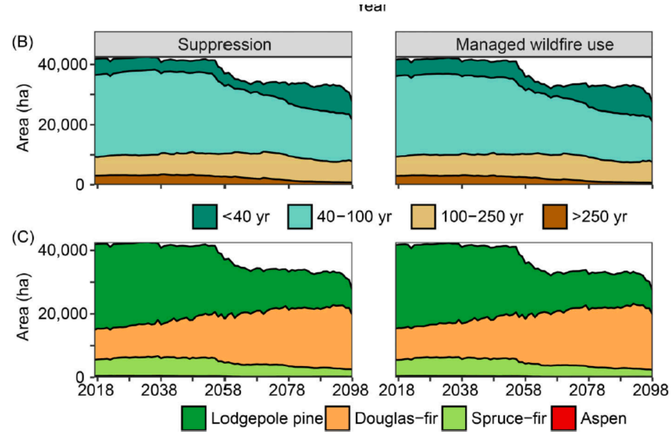
Fire suppression in 21st century subalpine forests of Greater Yellowstone
Monica Turner

Context: Warming and drying in subalpine forests of the western United States have caused large upticks in the number and area burned by wildfires. These trends should continue in the 21st century and the resilience of subalpine forests may be exceeded. How the suppression of subalpine fires might mediate 21st-century climate-fire trends has not been evaluated, however. Fire managers can effectively suppress smaller fires under average weather conditions, but larger fires that burn under drought and severe winds are not suppressible. Twentieth-century observations suggest that suppression of subalpine fires has not influenced subsequent fire size or forests–unlike in dry conifer forest types.

Aims: We used iLand to assess whether 20th-century observations hold under 21st-century conditions by characterizing *how a contemporary subalpine landscape would be different if fires had not been suppressed over the last three decades and how letting fires burn affects 21st century fire and forests.* We simulated a ~60,000-ha forest landscape in Grand Teton National Park from 1989-2099 with one scenario in which all fires were suppressed when weather conditions were average and another scenario where all fires burned without suppression. We compared cumulative area burned, percent non-forested area, forest age, and tree-species composition.

Results:

- On average, 200 more ha yr^{-1} burned when fires were not suppressed between 1989 and 2017. Forests changed little by 2017, with or without fire suppression.
- In the 21st century, cumulative area burned grew faster when fires were not suppressed. By 2099, almost twice as much area had burned.
- Climate change had a stronger effect on 21st-century forests than fire suppression.
    - By 2099, young stands made up ~85% of forested area, irrespective of suppression.
    - Lodgepole pine dominance declined as Douglas-fir dominance increased (Figure).
- Approximately 35% of stockable area became non-forested by 2099.
- Fire suppression could reduce 21st-C burned area but may only have a small effect on forests. Climate change (via fire) will likely be far more important.
- Results suggest management flexibility to strategically suppress subalpine fires, with few long-term consequences for 21st-C forests.

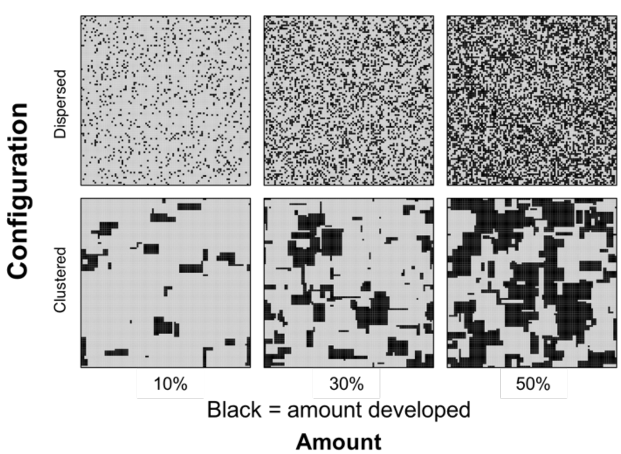


***Citation**: Hansen, W. D., D. Abendroth, W. Rammer, R. Seidl, and M. G. Turner. 2019. Can wildland fire management alter 21st-century fire patterns and forests in Grand Teton National Park? Ecological Applications e02030.*

Wildfire risk in the wildland urban interface: Effectiveness of defensible space management depends on development amount and configuration

Kristin Braziunas

Context and aims: The rapidly growing wildland urban interface (WUI), where structures meet or intermingle with undeveloped wildlands, comprises 10% of the land and one-third of the population of the contiguous US. Fire is expected to increase in nearly 40% of existing western US WUI in the next 20 years. Removing fuels in defensible space can reduce fire intensity, decreasing firebrand production and likelihood of structure ignition from radiant heat. Housing density and arrangement can also affect likelihood of structure loss. However, it is unclear how treatment effectiveness might change under future climate and fire conditions. For a subalpine forested landscape (10,816 ha) in the Northern Rockies, we used neutral landscapes, process-based modeling, and custom fire intensity and risk calculations to ask, *Which scenarios of WUI development minimize fire risk over the course of the 21st century?* We simulated defensible space treatment scenarios differing in the amount of landscape developed and therefore treated (10%, 30%, or 50%) and in development configuration (dispersed based on rural sprawl, clustered based on conservation development) under three 21st-century climate projections.



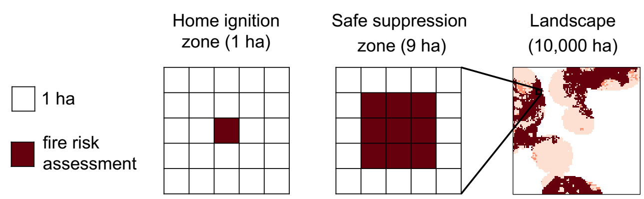


Figure (left). We simulated six development scenarios differing in amount and configuration.

Figure (above). We quantified fire risk at 3 scales to represent potential structure ignition due to direct flame contact or radiant heat (home ignition and safe suppression zones) or due to embers (landscape).

Key findings:

- Area burned increased regardless of treatment.
- Under warm-dry climate projections, the proportion of area that burned at high intensity declined by the end of the 21st century, coinciding with decreasing surface and canopy fuel loads across the landscape.
- Defensible space treatments consistently reduced fire risk in the home ignition zone regardless of amount and configuration.
- Clustered development configurations were more effective than randomly dispersed configurations at reducing safe suppression zone exposure.
- Treating 30% of the landscape was required to reduce fire risk at landscape scales.
- Defensible space management plays an increasingly important role in altering local and landscape-level fire intensity and structure loss as fire activity increases in western subalpine WUI.

Unpublished data (please do not cite)*: Braziunas et al. in prep*

Threats and benefits: Wildfire risk and ecosystem services under future climate and management scenarios

Kristin Braziunas

Context and aims: As climate conditions and fire activity depart from historical baselines, strategies that enable adaptive resilience in forested WUI landscapes will become increasingly important but are not yet well developed or tested. Adaptive resilience is the ability of people to manage for change and therefore maintain resilience in social-ecological systems. Forest disturbances and management actions may produce synergies or trade-offs among threats, such as fire risk, and ecosystem services, which are the benefits people derive from nature. In this study, I will simulate proposed management strategies for maintaining resilience under 21st-century climate and fire in forested landscapes surrounding two WUI communities: West Yellowstone, MT and Hamilton, MT. I will ask *(1) Which management strategies support adaptive resilience under future climate and fire?* and *(2) How do trade-offs and synergies among threats and services change over time and vary among management scenarios?*

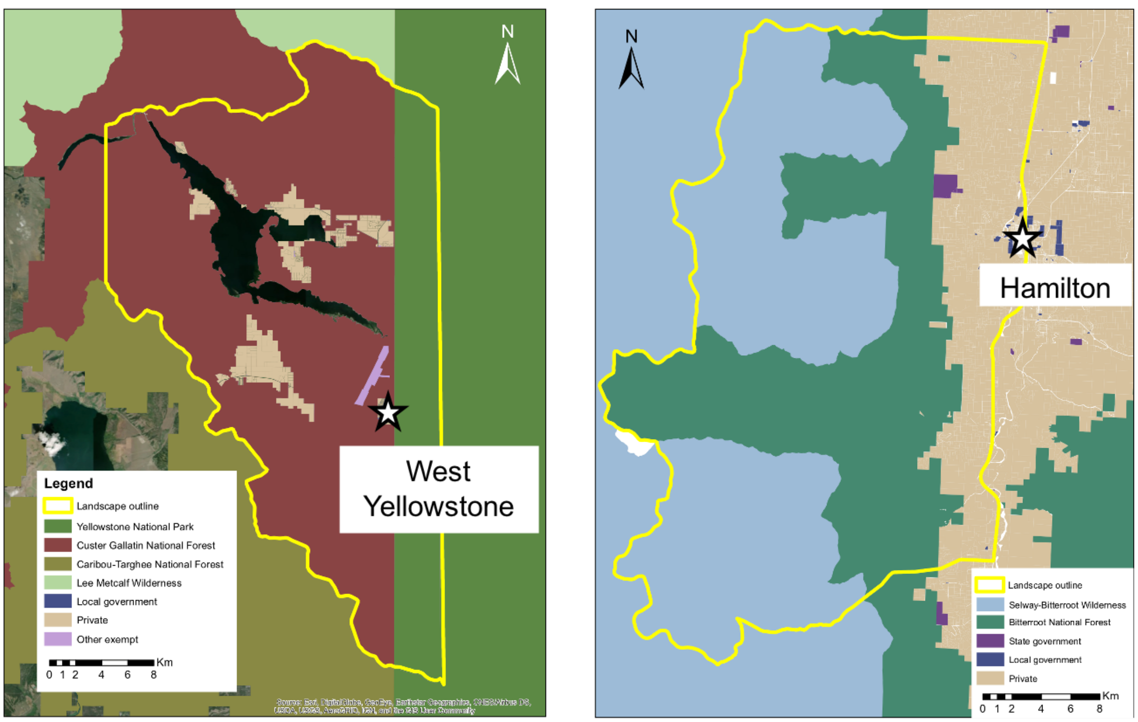


Figure. WUI landscapes in this study are oriented around West Yellowstone, MT in Greater Yellowstone (left) and Hamilton, MT in the Bitterroot Valley (right). These landscapes have different mixes of land ownership, forest types, and fire regimes but share similar challenges in managing fire-prone forests for multiple objectives.

Questions for discussion

1. Should any threats/services be removed or added to this list? Which ones are most important or interesting?
2. Are the indicators and desired conditions appropriate? Are there any other resources we should use to determine desired conditions?
3. Which management strategies would you expect to maximize resilience for each threat or service?

Table. Threats and desired forest ecosystem services in West Yellowstone and Bitterroot landscapes, identified based on workshops with fire and land managers in February 2017 and on Forest Plans.

Threat or service	Measurable indicator(s)	Desired conditions
Threats: Fire risk to...		
Structures	High intensity fire in home ignition and safe suppression zone	
Developed or privately-owned area	Fire spread and intensity near developments, in landscape	Minimize risk
Recreation	Overlap of fire spread with roads, trails, campgrounds, other recreation areas	
Water supply	High intensity fire in municipal watersheds	
Ecosystem services		
Timber and forest products	Harvest volume, Standing live stem volume, Density of trees by size class	Sustained yield, Volume/size classes within baseline range of variation (baseRV)
Climate regulation	Total live and dead carbon, net primary productivity	Within baseRV
Aesthetics (scenic character)	Forest cover, Proportion of forest in structure/age classes	Maintain forest area, Variability in forest structure and age classes per Forest Plan

Potential management strategies

- Fuels thinning
- Prescribed fire
- Fire suppression
- Fire use
- Timber harvest
- Tree seeding/planting

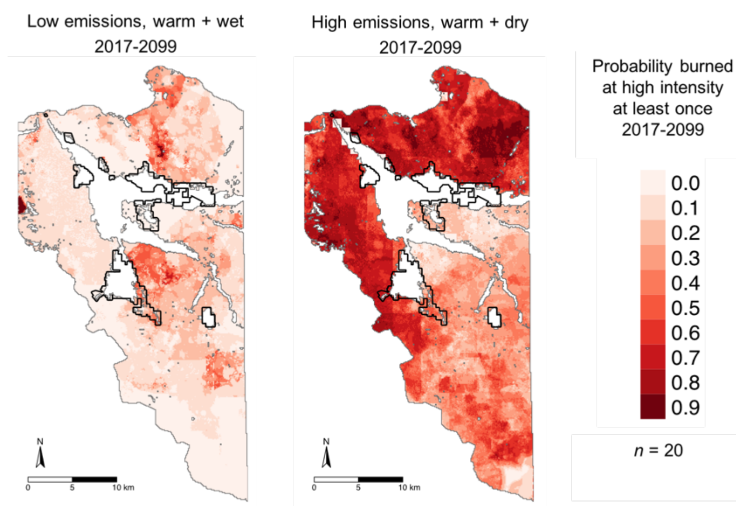


Figure (right). Example threat, fire risk to privately-owned areas. Under the high emissions, warm + dry scenario, almost all privately-owned area is likely to be exposed to fire at least once between 2017-2099.

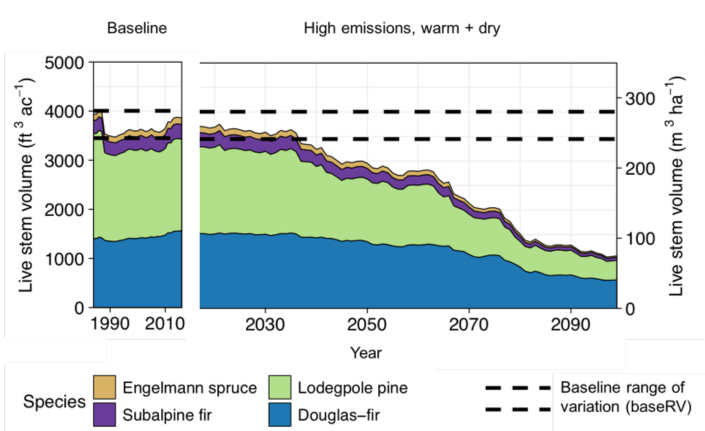


Figure (left). Example service, timber and forest products supply, quantified as the live stem volume by tree species throughout the landscape. In the high emissions, warm + dry scenario, supply declines substantially compared to the baseline range of variation across all species.

SCALING TO THE REGION

Projecting forest transitions

Rupert Seidl, Werner Rammer, Kristin H. Braziunas, Winslow D. Hansen, Zak Ratajczak, Leroy Westerling, Monica G. Turner

To project regional-scale forest transitions we developed a new simulation approach that is able to dynamically scale our stand- and landscape-level projections to larger spatial scales. The starting point was a state-and-transitions approach, because of their efficient application at large spatial scales. Yet, state-and-transition models often suffer from a coarse resolution in terms of the vegetation states considered and an inconsistent parameterization of transition probabilities. The approach developed here, called SVD (Scaling Vegetation Dynamics, Rammer & Seidl, 2019), overcomes these limitations by considering a large number of current and potential future vegetation states, and by basing transition probabilities on simulation results of the process-based model iLand (Seidl *et al.*, 2012). The results of detailed process model runs are assimilated into SVD via deep learning, which is an emerging machine learning approach that is at the core of many current applications of artificial intelligence. SVD operates at a spatial grain of one hectare and has an annual time step. The model is driven by the climate and fire projections generated by Westerling *et al.* (2011), and simulates fire spread spatially explicitly following the approach used in iLand.

In a first application of SVD, we simulated a forest area of 2.9 Mill. ha in the Greater Yellowstone Ecosystem (GYE), estimating the probability for vegetation transitions during the 21st century. Specific questions were (i) how early-seral forest area changes over the coming decades, (ii) how much of the currently prevailing forest types experience regeneration failure, and (iii) where spatial hotspots of likely regeneration failure are within the GYE. Early-seral forest area increased throughout the 21st century in all simulated scenarios, exceeding 800,000 ha in the most extreme scenarios. Sizable areas on the Yellowstone Plateau reburned twice or more until the year 2100. Dominant forest types failed to regenerate in up to 20% of the areas they currently occupy. Douglas-fir and Engelmann spruce – subalpine fir forest types had particularly low resilience to future climate and fire regimes, with 41% and 31% of the area burnt in these forest types failing to regenerate.

Citations

Rammer, W. & Seidl, R. (2019) A scalable model of vegetation transitions using deep neural networks. Methods in Ecology and Evolution, ***10****, 879–890.*

Seidl, R., Rammer, W., Scheller, R.M. & Spies, T.A. (2012) An individual-based process model to simulate landscape-scale forest ecosystem dynamics. Ecological Modelling, ***231****, 87–100.*

Westerling, A.L., Turner, M.G., Smithwick, E.A.H., Romme, W.H. & Ryan, M.G. (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences of the United States of America, ***108****, 13165–13170.*